



Two-level refined direct method for electromagnetic optimization and inverse problems



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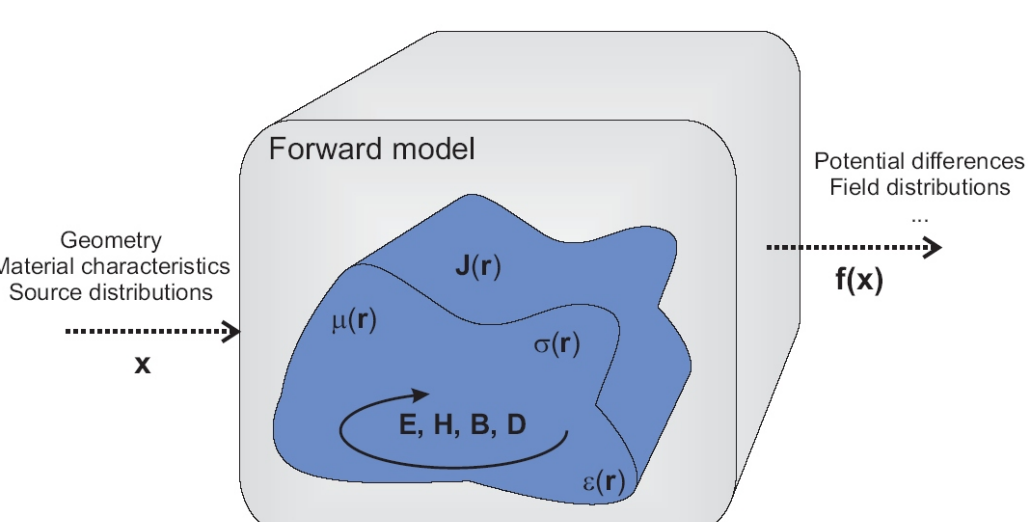
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Introduction

Forward electromagnetic models:

Numerical techniques (FEM, FDM,...)
CPU-time mainly depends on discretization
CPU-time demanding



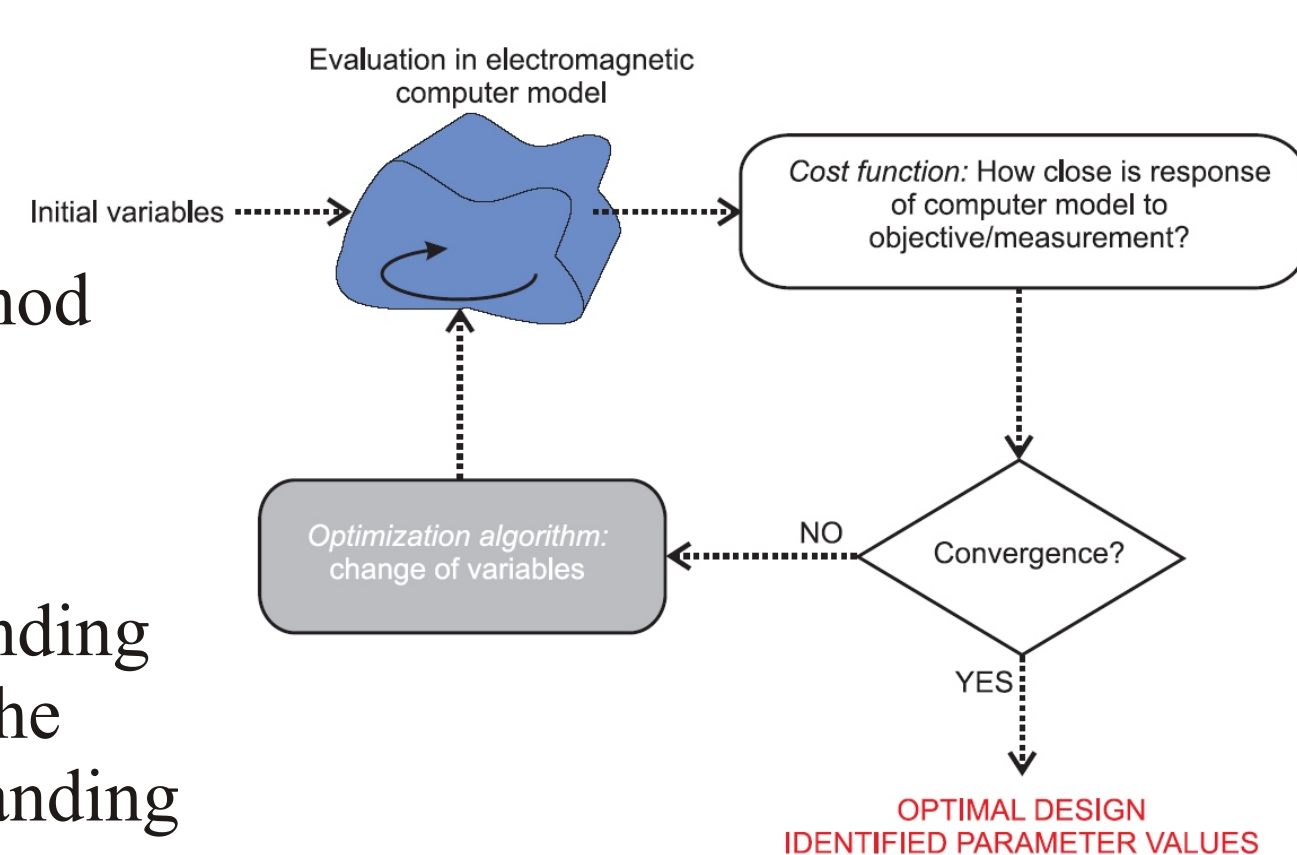
Electromagnetic Optimization and Inverse Problems:

Direct minimization method:

- Iterative solution procedure
- Update of variables depends on method

$$\mathbf{x}_f^* = \arg \min_{\mathbf{x}} \mathcal{Y}(\mathbf{f}(\mathbf{x}))$$

Traditional methods are CPU-time demanding because many iterations are needed and the forward model evaluations are time demanding



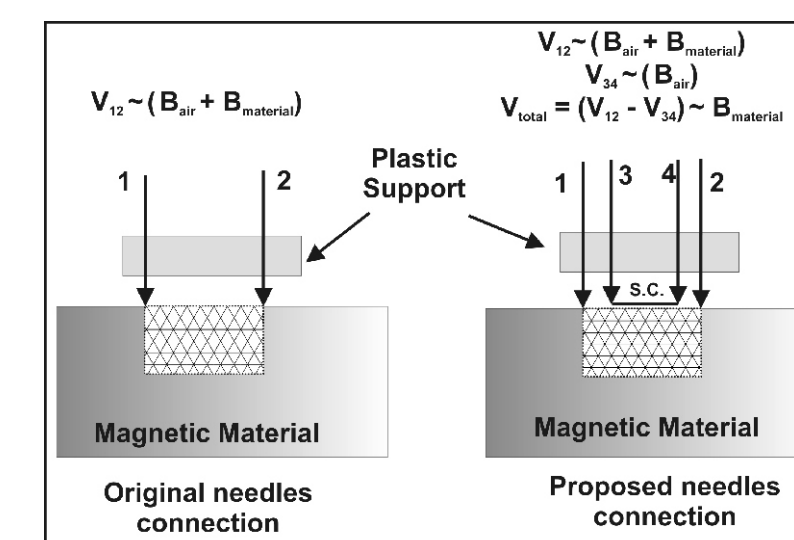
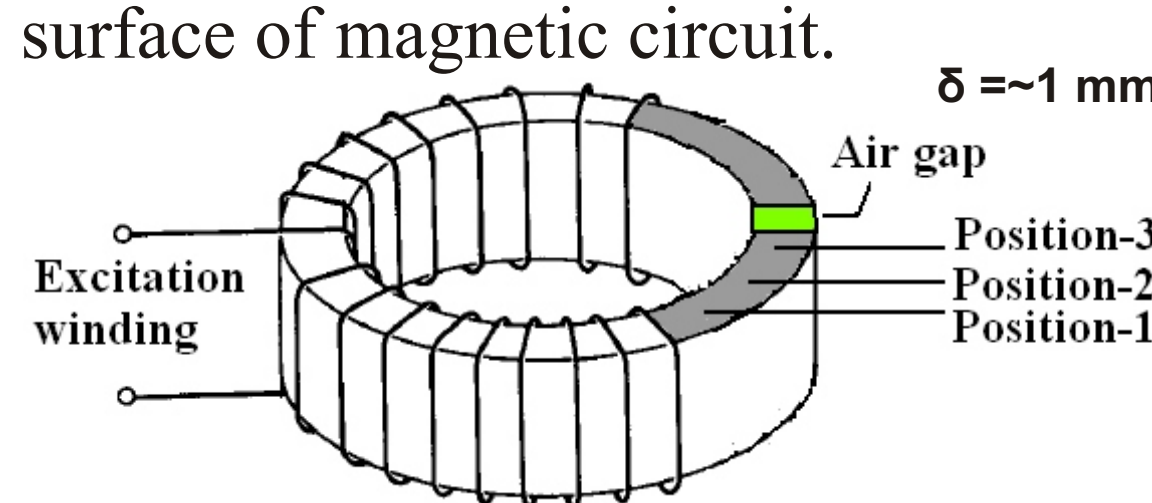
→ Include models with different levels of fidelity into the iterative procedure

Magnetic material characterization

Problem: Magnetic materials of electrical machines are often not known.

Solution: Identify the material characteristics by solving an *experimental-numerical coupled inverse problem*.

- **Experiments:** Local magnetic induction measurements: *needle probe method* that measures potential differences, which depend on magnetic material characteristics, on the surface of magnetic circuit.



Improved magnetic measurement technique

- **Numerical method:** Finite element method with *input*: excitation current, material characteristics. *Output*: Needle voltage signals.

Validation of procedure: Identify the material characteristics on a ring core (simplified electrical machine) with known geometry and material characteristics.

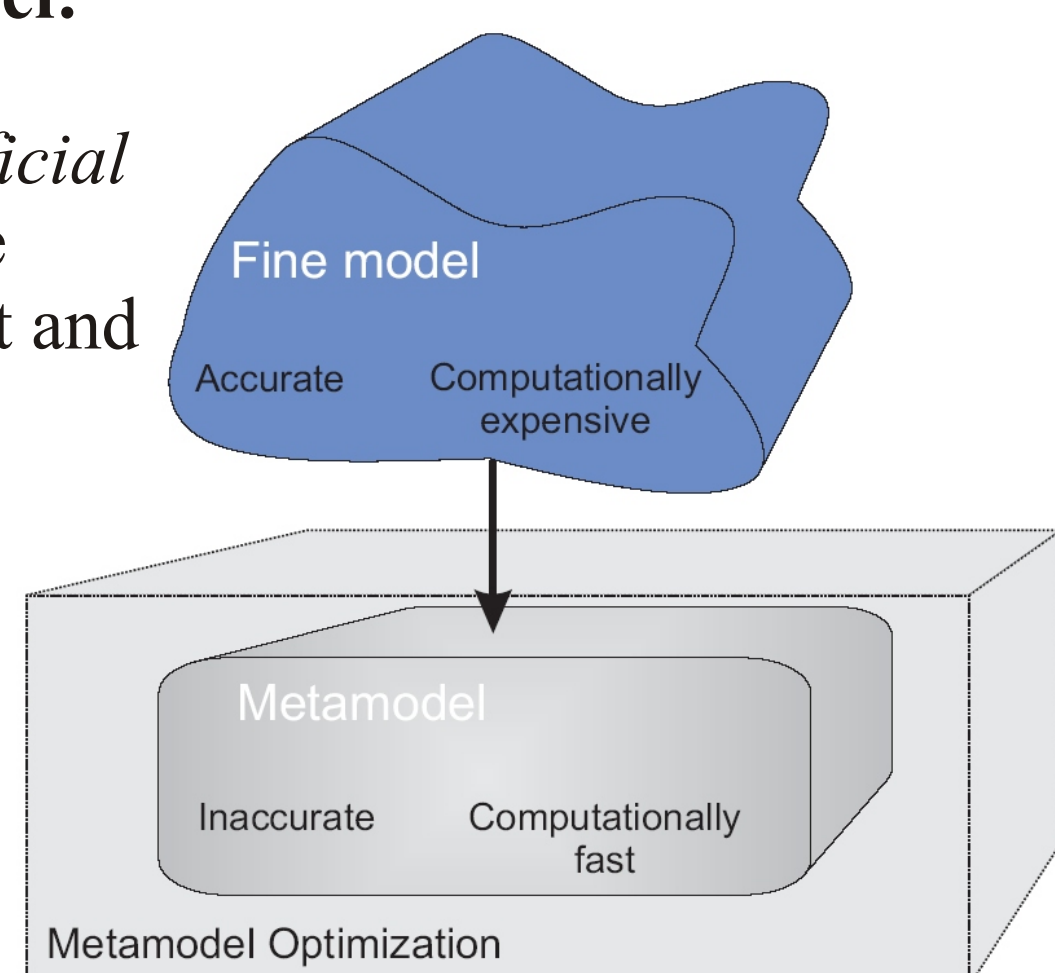
Two-level refined direct method

Construction of metamodel based on forward model:

- *Metamodel (Response Surface Model, Kriging, Artificial Neural Network)* can be constructed from a CPU-time expensive forward model by fitting 'off-line' the input and output space of forward model.

- *Design of experiments* determines which parameter values to evaluate in fine model.

- *Optimization* can be carried out using this computationally fast metamodel.



- During optimization, the metamodel can be refined by additional fine model evaluations, see e.g. Efficient Global Optimization (EGO) algorithm.

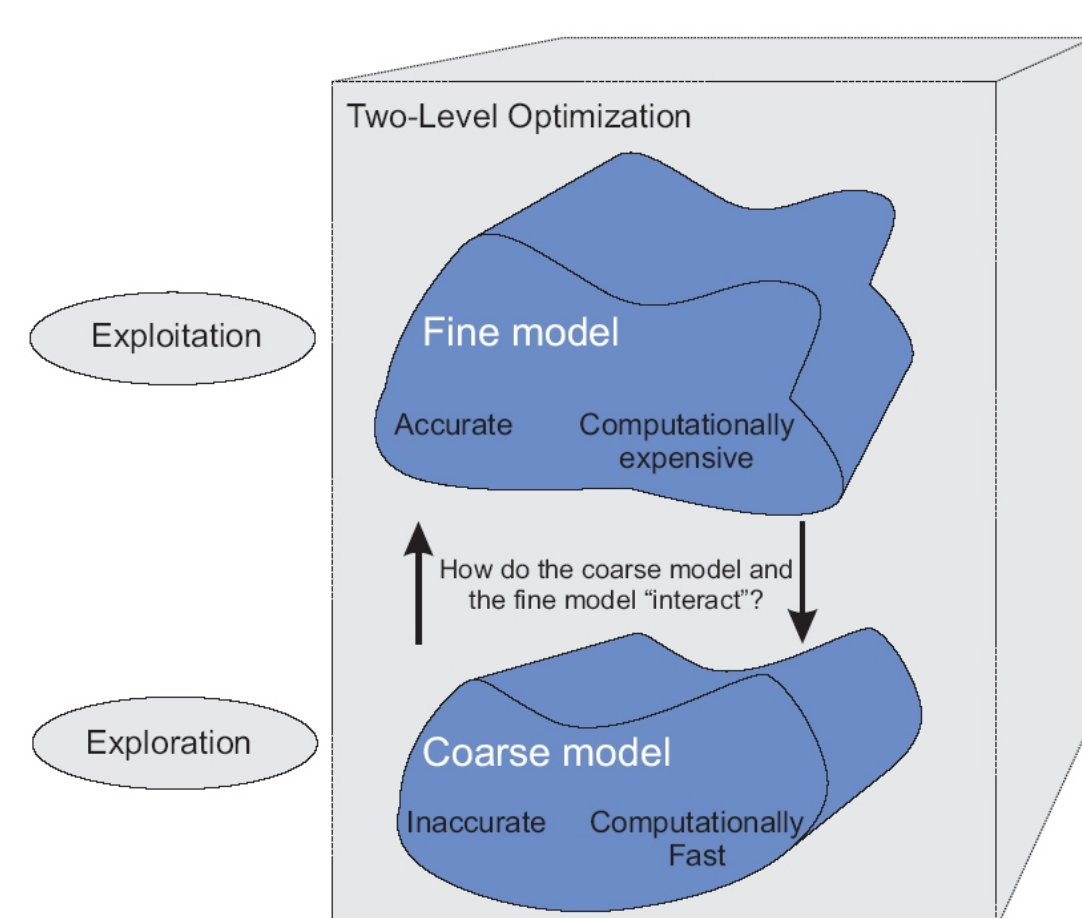
→ Difficult when dealing with high-parametric models and with high-nonlinear models

Two-level minimization methods:

- *Coarse model:*

- approximation of fine model (analytical, coarse discretizations of numerical method, ...)
- physics-based model
- Non-linearities of fine model are also available

- Space mapping, manifold mapping, response and parameter mapping: Iterative minimization of coarse model for different objectives



→ CPU-time demanding when coarse model is not sufficiently faster than fine model. This is the case when coarse model = fine model with coarse discretization.

Two-level refined direct method:

- Use of 3 models: *coarse model*, *fine model*, *metamodel*

Build computer models:
Fine model: fine discretizations
Coarse model: coarse discretizations

Coarse model can be easily build by using a low number of discretizations in the numerical fine model

- Metamodel interpolates between coarse and fine model outputs. The high-nonlinearity and high-parametric fine model is approximated by the following *surrogate model: metamodel-corrected coarse model*.



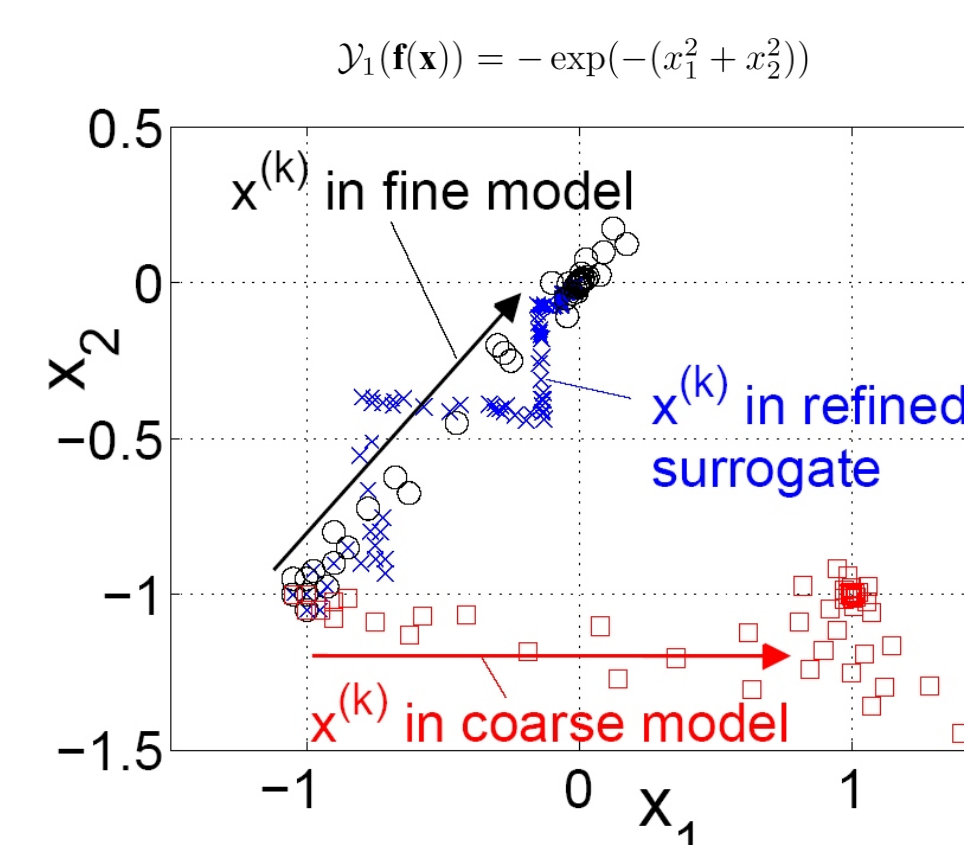
- Surrogate model is used in each iteration of the direct minimization method. The surrogate model is *refined* during the iterative procedure.

- *Trust region strategy* for determining when surrogate model needs to be updated.

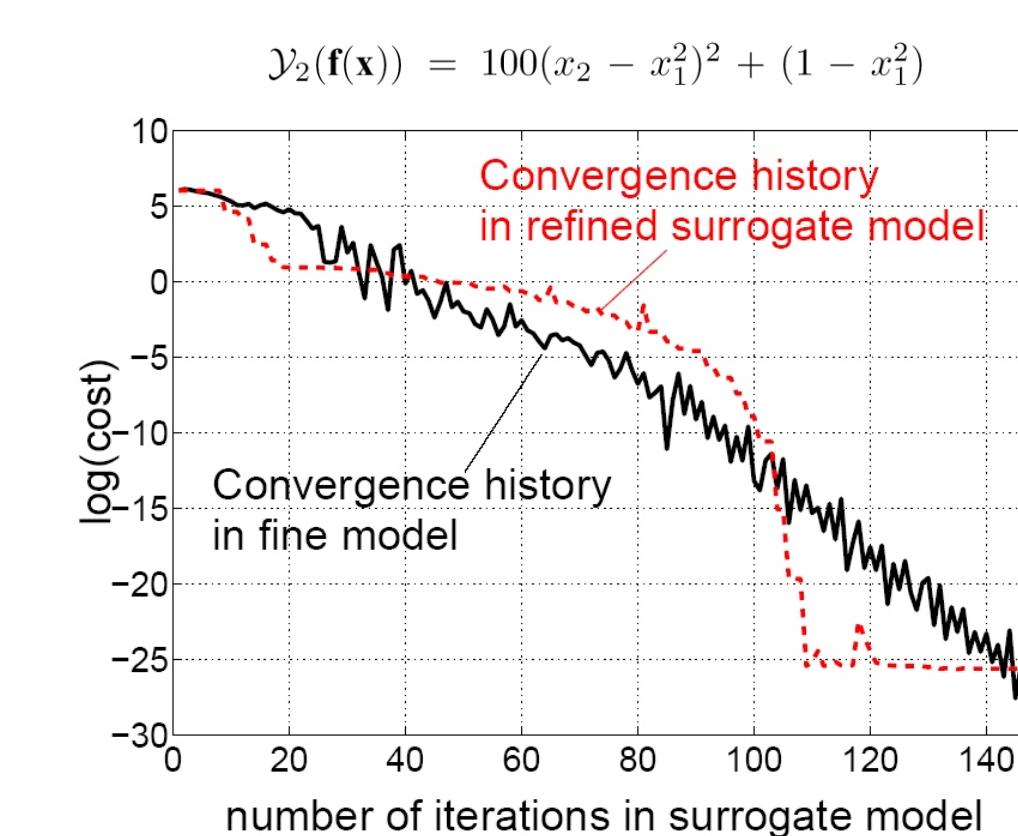
→ CPU-time efficient solutions of electromagnetic optimization and inverse problems for highly nonlinear problems and high-parametric optimization problems

Results and discussion

Application of algorithm on algebraic test functions:



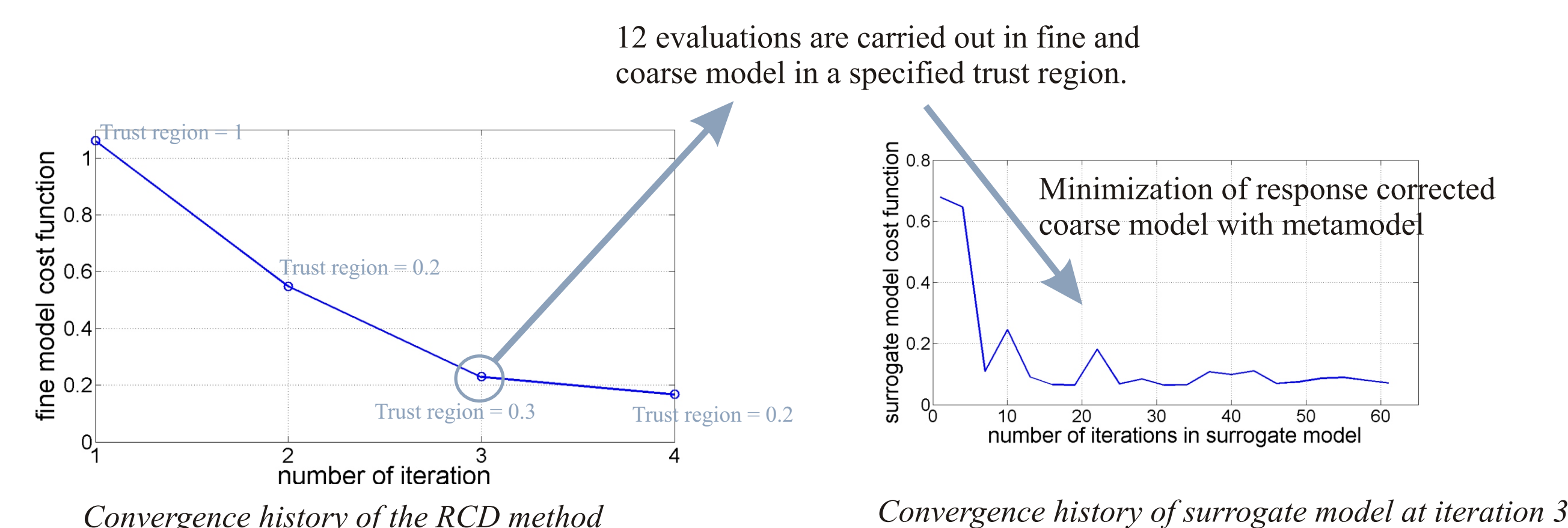
Fine model: exponential model, optimal value [0,0]
Coarse model: altered fine model, optimal value [1,-1]
Metamodel: Kriging model



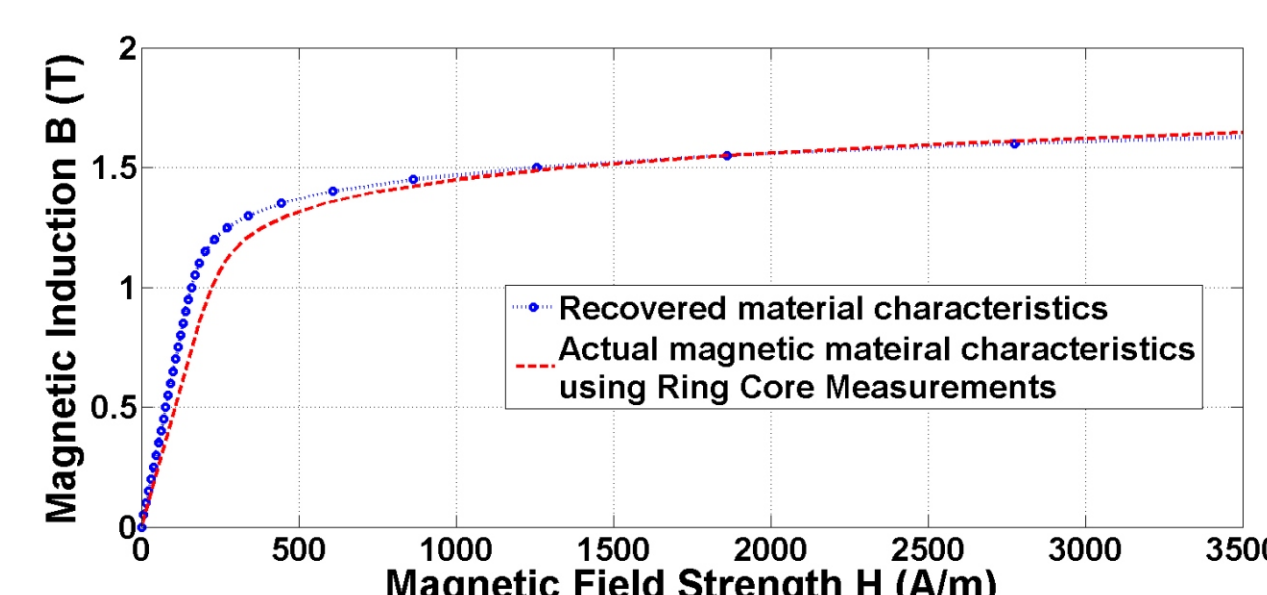
Fine model: 2D-Rosenbrock function
Coarse model: altered fine model
Metamodel: Kriging model

Application of algorithm for magnetic material reconstruction:

Single-valued nonlinear constitutive relation of magnetic material is determined by $[H_0, B_0, v]$: $\frac{H}{H_0} = \left(\frac{B}{B_0}\right) + \left(\frac{B}{B_0}\right)^\nu$



Recovered BH-characteristics using RDO-scheme:



Validation of the proposed method: Recovered material characteristics are close to actual material characteristics of the magnetic circuit

Errors are due to noise in measurements and errors in forward modelling

Computational time: 60 fine model evaluations, 264 coarse model evaluations

Advantages:

- + Parallel computing is possible in a sequential direct minimization scheme
- + Initial computation using coarse model can be used as preconditioner for fine model
- + Fast optimization scheme

Conclusions

- Two-level refined direct method is efficient for optimization and inverse problems with forward models that are CPU-time demanding
- Coarse models for RDO can be easily constructed: fine model with coarse discretizations
- Acceleration for recovering the inverse solution
- BH-characteristics of a magnetic circuit can be obtained by interpreting the local magnetic measurements using an inverse procedure
- Validation of an experimental-numerical coupled inverse procedure for magnetic material characterization